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ARCTIC ICE-ISLANDS AND HOW THEY DRIFT *

Professor N. N. Zubov

In recent years there have been discovered, in the Central Arctic Ocean, some very curious ice-formations, known as ice-islands. These islands are sharply distinct both from the old ice-fields of the Central Arctic regions and from the icebergs calved by the glaciers which descend into the Arctic Basin.

The shape (as viewed in plan) of the ice-islands is nearly oval. Their horizontal and vertical sizes are very large; they have areas of as much as hundreds of square kilometers, and rise 10 to 15 meters above the level of the ordinary floating sea ice. But the chief peculiarity of ice-islands is their corrugated surface. They may have, along their whole length, ice-ridges in almost parallel rows with crests at a distance of 300 to 1000 meters from each other. As observations over several years have shown, the ice-islands remain practically unchanged in shape and size, the fact which proves their great thickness and strength.

These massive ice islands, along with other smaller ones, were first sighted in the Central Arctic Basin by Soviet polar airmen; by I. S. Kotov in March 1946, in the region northeast of Wrangel Island; by I. P. Mazuruk in April, 1948, at 82°N 170°E; by V. M. Perov in March, 1950, in the region northeast of Herald Island.** Kotov's Island was 30 km long, 24 km wide, and more than 600 square km in area. Mazuruk's was 32 km long, with a width of 28 km, and Petrov's was 17 by 8 km.

The thickness of the Arctic ice fields (including the hummocks) usually does not exceed 3-5 meters, while the horizontal dimensions both in summer and particularly in winter may be very great (some tens of kilometers). Most of the East Greenland icebergs which have been surveyed had heights of about 70 m and lengths around 1 km. Thus the ratio of vertical to horizontal size is extremely small in ice fields, and in icebergs comparatively large. Ice islands occupy, in this respect, an intermediate position.

The ice islands discovered by the Soviet fliers were later noticed by U. S. airmen, and were given the name T-1, T-2 and T-3. Island T-1 as seen

* Various opinions exist on ice-islands and their drift. In publishing this article by Professor Zubov, which sets forth one of these opinions, it is the Editors' intention to give publicity, later, to other points of view on these questions.

** See V. Burkhanov, New Research by Soviet Scientists in the Arctic, "Pravda", May 16, 1954.

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from the air had an appearance so suggestive of ordinary Arctic islands that this was what it was taken to be. Soon, however, it became apparent that this "island" was changing its position.

In 1950 the U.S. airforce carried out a special search for ice-islands in the sector between 30° and 180° West, and in 1952 they established an air field and meteorological station on T-3.* At the same time, many ice-islands of smaller size were discovered during special flights, off the northern coast of Ellesmere Island and also in the straits of the Canadian Arctic Archipelago.

Naturally this gave rise to the question of just where or when the ice-islands were formed. The initial idea was that ice-islands were fragments broken off from glaciers descending into the sea; that is, icebergs. This hypothesis was seemingly supported by finds of massive boulders and other moraine deposits on the surface of the ice-islands. However, there are at the present time no glaciers on the shores of the Arctic basin which could produce icebergs of such great area.

In fact, icebergs in the Arctic basin may come only from Spitsbergen, Franz Josef Land, the North Island of Novaya Zemlia, and also the northwest coast of Greenland and the northern coast of Ellesmere Land, since only here are there glaciers descending to sea level.

The fronts of the glaciers on Spitsbergen, Franz Josef Land, Novaya Zemlia and Severnaya Zemlia have no great height; neither are the adjacent waters very deep. Therefore the length of icebergs calved in the eastern Arctic longitudes are measured only in tens of meters; in rare cases, hundreds of meters.

In the American sector of the Arctic, the possible sources for which might supply icebergs to the Arctic Basin are the glaciers in the fjords of the northwest Greenland coast. Here the glacier fronts and the adjacent sea depths are greater than in the eastern hemisphere. Nevertheless, the North Greenland icebergs similarly cannot have lengths exceeding a few kilometers.

Thus it appears that the huge ice-islands discovered in the Arctic Basin, the narrowest width of which is measured in tens of kilometers, are not icebergs produced by any glaciers of today.

In 1950 American ** airmen photographed, under good weather conditions, the ice-shelf on the northern coast of Ellesmere Land (Fig.1). It was found that the surface of the shelf-ice, which extends along the northern shore of Ellesmere Land for at least 90 km and to a width of 18 km, is corrugated and very similar indeed to the surface of Ice-islands T-1, T-2 and T-3, particularly that of T-3, the youngest.*** The ice islands which had

* The station was evacuated in May, 1954, for the reason, according to American statements, that it had drifted close to stations on the mainland.

** Canadian! (Translator.)

***The American scientists' comparison of the drift courses of the ice-islands assumes that T-3 broke off from the shelf-ice and began its drift only in 1946.

broken away earlier had a more even surface. On T-1 the tops of the ridges rose only 0.6 to 0.9 m above the valleys, and on T-2 still less. It may be supposed that in time the surface of ice-islands levels off. This is caused by thawing of the crests and freezing of the water which runs into the valleys.

One proof that it is the ice-shelf of the Northern Ellesmere coast that calves the ice-islands is found in photographs of an ice-island taken in 1947 off Cape Columbia (83°07' N, 70°10' W). Photographed at the same time was a portion of the corrugated shelf-ice at Cape Nares (83°05' N, 71°40' W). The perimeter of the ice-island fitted exactly into a gap in the shelf ice from which this island had broken off.

Photographs of the areas to the east and west of Cape Columbia showed that the ridge-crests on the surface of the shelf-ice ran approximately parallel to the shore line.

All this is proof that the ice islands are fragments of the characteristic corrugated shelf-ice on the northern shores of Ellesmere Land. However, the problem of the origin of this corrugated shelf-ice cannot yet be considered solved.

Some people regard this shelf-ice as a relic of ancient glaciation. At the present time, the glaciers in the northern part of Ellesmere Land do not come down to sea level, and are still retreating. The glacier origin of the ice shelf seems indicated by the presence of boulders and gravel on it, and on the ice-islands broken off from it; also by the layered ice-structure and great thickness of the ice-islands.

Others suppose that what we have here is old shelf-ice of marine origin.* Theoretically, as we shall show, the thickness of ice may under certain circumstances become as much as ten or more meters. Under certain circumstances boulders and stones may turn up even on shelf-ice of marine origin. Cases have occurred of ships in the Baltic Sea finding themselves surrounded by ice formed on the sea bottom; this ice contained sand and natural objects which it had brought up with it. The bottom ice on the rocky shores of Greenland, Labrador and Spitsbergen raises blocks of stone and earth to the surface of the sea. A case is known of a box of instruments being brought to the surface by bottom ice. This box turned out to have belonged to a vessel wrecked many years previously in Hudson Strait, some hundreds of miles north of the point where the find was made.** The layered structure is also characteristic of old shelf-ice, and is explained by seasonal phenomena, the same as the layered structure of glacier ice.

Finally, there are some who maintain that the ice-shelf is a conglomeration of glacier and sea ice fragments, piled up one on the other and welded together over a large interval of time into a single whole.

Old shelf ice may reach a great thickness. What is involved is that the increase in thickness of the sea ice (aside from hummocking) is usually

* C. F. Debenham. The Ice Islands of the Arctic, a Hypothesis. Geogr. Review, 1954.

** See N. N. Zubov. Morskiye Vody i L'dy [The Water and Ice of the Sea], Hidrometizdat [Hydrology and Meteorology Press], 1938, p.263.

greater, the smaller the initial thickness of the ice and the greater the sum of the mean below-zero air temperatures: in other words, the greater the number of degree-days of frost.

On the northern shores of Greenland and Ellesmere Land the number of degree-days of frost per winter is 8000. Let us assume that in the course of the summer the ice thickness decreases, through melting, by 40 cm, which is even a little exaggerated for the region in question. Then during the first winter (8000 degree-days of frost) the ice thickness, as calculated according to the author's empirical formula, * will reach 230 cm. During the summer this will drop to 190 cm. Next winter (8000 degree-days of frost) the thickness will increase from 190 to 330 cm, and in summer again it will decrease to 290 cm, and so forth. If we continue these calculations, we find that when the ice reaches a thickness of 755 cm an equilibrium is achieved; the growth in winter will be 40 cm, that is, as much as melts off in summer. To that thickness of ice at which just as much ice melts off in summer as grows on in winter, the name "ultimate thickness of old ice" was given by Weiprecht, one of the leaders of the Austrian expedition which discovered Franz Josef Land. This ultimate thickness serves as a good climatic index, defining both the winter and summer regime of the Arctic regions.

It is in the area of the north of Greenland and Ellesmere Land that we observe the maximum degree-days of frost ** and the minimum winter thaw in the Arctic Basin. The influence of the warm atlantic waters flowing into the Arctic Basin practically does not penetrate to these parts.

If we assume that with the same number of degree-days of frost, that is 8000, the summer melt in a certain region of the Arctic is half of the above amount, or 20 cm, then the ultimate thickness of the ice will be twice as much; that is, it will be approximately 15 m.

As already stated, these calculations are based on an empirical formula derived by the author from observations in the border-seas of the Soviet Arctic. Since the hydrometeorological conditions on the northern coast of Greenland are a good deal different from conditions in the Soviet Arctic, any calculated values for the ultimate thickness of the old shore ice must be regarded as very approximate. Nevertheless they do demonstrate that under suitable conditions the old shelf-ice may build up to a considerable thickness.

From this concept of the ultimate thickness we understand that if, for example, a floe 4 m thick is carried into a region where the ultimate ice-thickness is 5 m, then it will gradually build up to that thickness. If on the other hand this floe gets into a region where the ultimate thickness is 3 m, it will waste away accordingly.

Ice islands T-1, T-2 and T-3, after their break-away from the shelf ice of Ellesmere Land, were drifting in regions of considerably smaller ultimate thickness. Moreover drifting ice, other conditions being equal, melts away from below at considerably higher rate than ice which is at rest. Therefore the thickness of the ice-islands diminished as they drifted. This process was,

* See N. N. Zubov. Morskiye Vody i L'dy pages 334-342.

** On Grinnel Land (80°20' N 74° W) the mean annual air temperature is -20.4°C.

however, very slow. The only thing capable of accelerating it is the break-up of the ice-islands into pieces, through non-uniformity in their structure and non-uniformity in the various kinds of stresses to which they are subjected.

Glacier ice and old sea-ice, along with their features of similarity, have certain differences between them.

Glacier ice thickens on top (by snow-fall and hoar frost) and melts off underneath. Sea ice, on the contrary, thickens underneath and melts away on top. Consequently, foreign objects deposited on the surface of glacier ice gradually descend, while such objects which in one way or another find their way into sea ice rise gradually toward the top.

Snow falling on the surface of a glacier increases its thickness, whereas snow falling on marine ice floes prevents, by its low thermal conductivity, the growth of these floes. It has been shown by much observation in the Soviet Arctic Seas that in areas swept clear of snow the ice thickness, other conditions being equal, exceeds by half as much again the thickness of the ice in areas where the surface is snowed in.

The corrugated surface of the shelf-ice on the northern coast of Ellesmere Land had particularly attracted the attention of scientists. This waviness may be explained in several different ways. Those who argue for the glacier origin of the shelf-ice suppose that the parent glacier, descending into the sea, encountered obstacles in its path, which wrinkled and crumpled the surface into folds at right angles to the glacier axis.

At the present time there is a solid belt of corrugated shelf-ice extending parallel to the shore line for a distance of 90 km, from Cape Columbia to Yelverton Bay ($82^{\circ}20' \text{ N } 84^{\circ}00' \text{ W}$). The folds in the corrugated shelf-ice are parallel to each other. If we accept the glacier origin hypothesis, then we have to admit the existence in this region, in the past, of a glacier with a frontal width of not less than 90 km.

The shelf-ice might also be folded by the pressure of the ice on the open sea, moving shoreward perpendicularly to the coastline. The region on the north of Ellesmere Land where we find the corrugated shelf-ice is especially subject to pack-ice pressure. Indeed Peary, on his way north from Grant Land ($82^{\circ}40' \text{ N } 73^{\circ}00' \text{ W}$), found a great lead of open water at approximately $84^{\circ}30' \text{ N}$, blocking his route to the pole. This same open lead was later observed by Soviet and American airmen. It is formed when the wind is offshore (from the south). When the offshore wind changes to a shoreward (north) wind, the masses of ice pick up speed, crush in against the shelf-ice, and crumple it into folds.

Corrugation of the shelf-ice could also be due to large fluctuations in the temperature of the ice. The temperature of the lower surface of ice, when it is afloat, is always close to the freezing point, while on the top surface it fluctuates, in the course of the year, over a range from zero to $40-50^{\circ}$ below zero [centigrade]. If we take it that the ice-shelf is at some points resting on the bottom so that its lower surface is immovable, then temperature fluctuations might cause either fissures or folds in the ice, and here again they will be parallel to the shore line.

However, it is not yet possible to regard the formation of the corrugated shelf ice as adequately explained. Furthermore we do not know by what process the ice-shelf is broken up to form ice-islands. Possibly what is involved is syzygial tides (at new or full moon), baric * and seismic waves, tidal phenomena. Soviet Arctic-men have repeatedly observed ice-fields to crack without visible cause, the line of the break running almost in a straight line both across level spots and through hummocks, as though the thickness of the ice meant nothing as far as the fissure was concerned.

After splitting off from the shelf, the ice-islands are by degrees pulled into the ocean eddies, and sometimes turn up very far away from their place of origin. In this connection it is possible to draw certain analogies between the drifts of ice-islands broken off from the shelf-ice and the so-called "iceberg eruptions", the causes of which are still not adequately explained.

Thus, for instance, in May 1929 some small icebergs, no doubt from the glaciers of Franz Josef Land, showed up off the Murman coast, and by June were at Cape Kanin. A remarkable fact about this drift was that on their way from the shores of Franz Josef Land these icebergs had cut across the North Cape current.

In the same year 1929 the number of icebergs sighted to south of Newfoundland exceeded by almost three times the number of icebergs seen in that area both before and after 1929. That is to say, in 1929 an "iceberg eruption" was observed simultaneously in the Barents Sea and in the area south of Newfoundland. In 1939 and 1940, similar "iceberg eruptions" were observed in the regions adjacent to the southwest and southeast coasts of Severnaya Zemlia.

In March 1943, hundreds of icebergs were discovered in the region north of Franz Josef Land, between 84° and $84^{\circ}30'$ N. Yet in the many flights made by Soviet aircraft over approximately this route during the establishment of Station North Pole in 1937, not one iceberg was sighted. According to my calculations, these icebergs had been brought from the Severnaya Zemlia region by the winds. In October of this same year 1943, at 3 km northwest of Cape Molotov, an iceberg of tabular shape was discovered, 1500 m long, 400 m wide, and standing 10 m high above the level of the water.

What is even more surprising, some icebergs, stranded in shoal water, were discovered in 1946 on the eastern coast of Wrangel Island, and in 1947 on the western coast. No-one had previously seen icebergs off Wrangel Island.

Calculation showed that these icebergs had likely been carried there from the northwestern shores of Greenland.

According to several years' observational data, the ice-islands drift in complicated and irregular orbits. These orbits start in the region of Cape Columbia, run parallel to the northern shores of the Canadian Archipelago in the direction of Point Barrow ($71^{\circ}21' N$ $156^{\circ}40' W$), then turn north and return toward Cape Columbia via the higher latitudes. Thus they describe clockwise orbits, dependent on the general ice circulation and water circulation in the Arctic Basin and its border-seas (Fig.2).

* Waves in the sea due to barometric pressure differences. (Translator.)

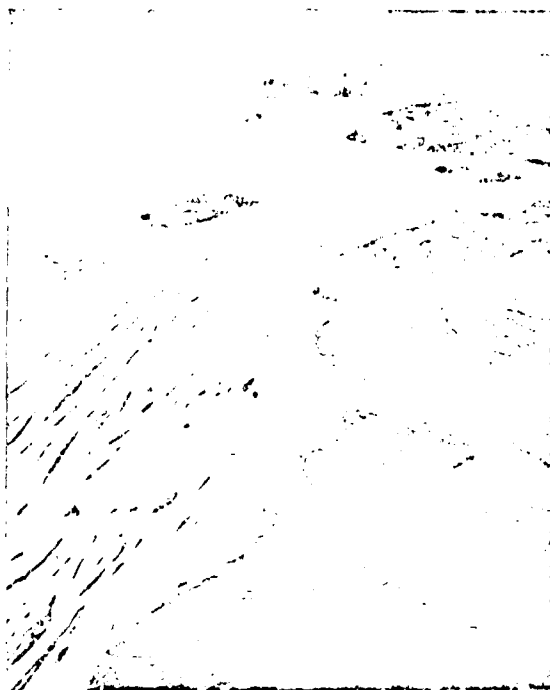
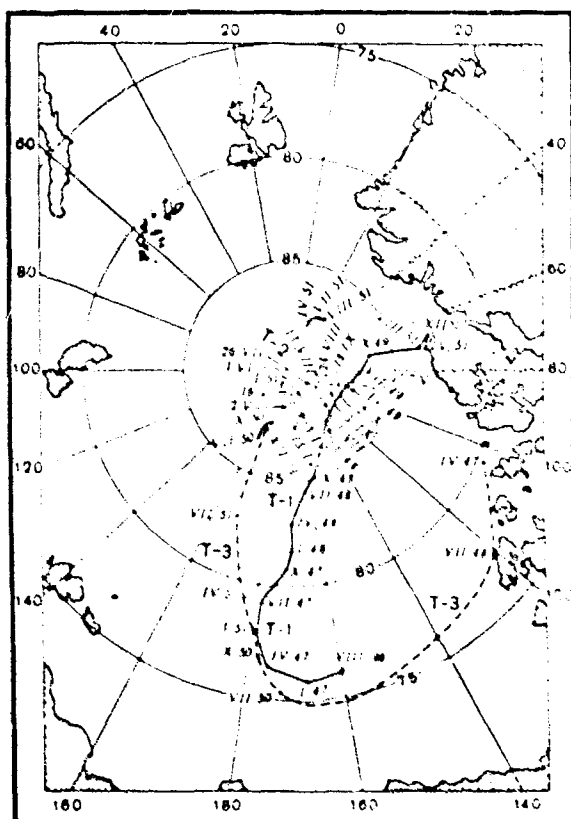


Fig.1. Old shelf-ice along the northern coast of Ellesmere Land, July 16, 1950, showing the characteristic corrugated surface. (Photo from Journal of the Arctic Institute of North America, July, 1952, Vol.5, No.2.)

NOT REPRODUCIBLE



— T-1 - - - T-2 . . . T-3

Fig.2. Drifts of ice-islands T-1, T-2 and T-3.

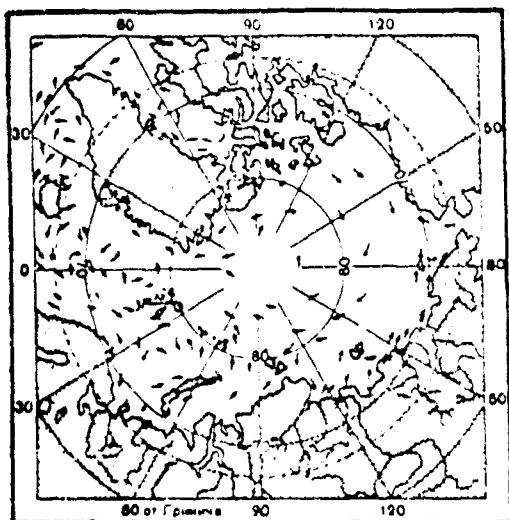


Fig.3. Ice drift and surface currents in the Arctic Ocean.

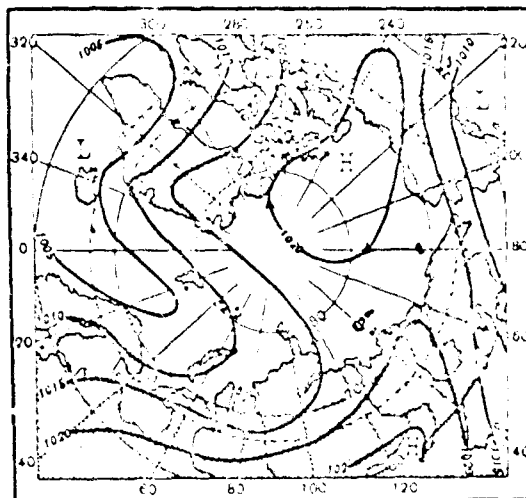


Fig.4. Mean atmospheric pressure (in millibars) in the Central Arctic in winter.

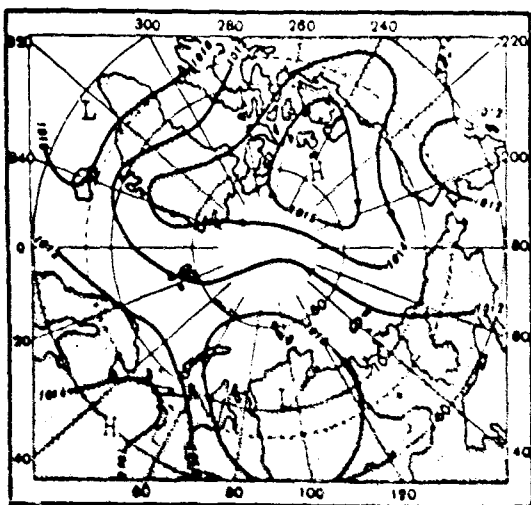


Fig.5. Mean atmospheric pressure (in millibars) in the Central Arctic in summer.

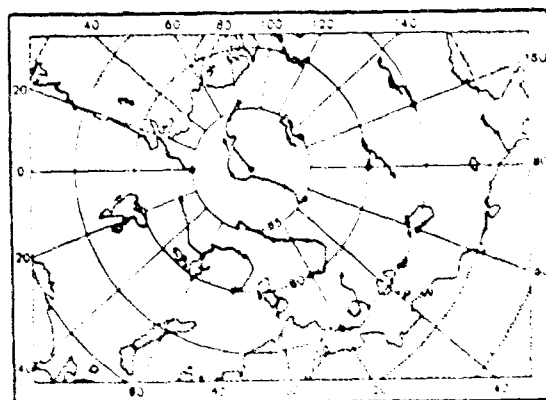


Fig.6. Calculated drift of arctic ice in 1930 (after N. N. Zubov and M. M. Somov).

It is now solidly established that in all the Soviet Arctic border-seas, as in all other seas of the northern hemisphere, the basic ice circulation is counter-clockwise, and that more ice is carried out of the seas into the Central Arctic Basin than what gets back there again (Fig.3).

In the central part of the Arctic Basin, there exist two basic systems of ice movement. One of these involves the efflux of ice from the Arctic Basin into the Greenland Sea, and is due to the shore run-off, to the inflow of water from the Norwegian Sea, driven by southwest winds, and to the transport of water and ice from the Arctic Basin into the Greenland Sea by the northeast winds which prevail along the eastern coast of Greenland. The other system is an anticyclonic (clockwise) eddy with its center at approximately 82° N and 120° W. This eddy is due to winds connected with the high-pressure area over the Canadian Archipelago.

As early as 1763, M. V. Lomonosov * was writing about the east-to-west movement of the ice in the Arctic Basin and, as we know, the correctness of his ideas has been confirmed by all known ship-drifts. Thus the Mariuk in 1913-1914 drifted with the ice from around Point Barrow in Alaska to Wrangel Island. The Jeannette in 1879-1881 drifted from Wrangel Island to the New Siberian Islands. The Fram in 1893-1896 drifted from the New Siberian Islands to the straits between Greenland and Spitsbergen. The Maud in 1922-1924 drifted from Wrangel Island to the New Siberian Islands. It is worthy of note that the Maud's drift reproduced almost completely that of the Jeanette, and the drift of the auxiliary icebreaker G. Sedov (1937-1940) almost completely that of the Fram.

The continual movement of the ice from east to west along the Eurasian continental shelf is also proved by observations made during the sledge expeditions of Parry (1827), Nansen (1895), Cagni (1900), and on the American continental shelf, by Stefansson (1913). This same movement is evidenced by the fact that remnants of articles from the Jeannette, which was lost off the New Siberian Islands, have been found on the coasts of Greenland, Iceland and Norway; also by the courses of buoys set adrift on the water and on the ice by Soviet expeditions. Thus the ice-drift is in an unbroken line around the periphery of the Central Arctic Basin from 160° W through all the eastern longitudes to meridian 0° . It is also known that ice from north of Peary's "big open lead" which extends along latitude $84^{\circ}30'$ N between Grant Land and the North Pole, drifts into the Greenland Sea, while the floes south of this lead are now and then subject to severe pressure of the pack-ice driving against them. Finally, the drift of Station North Pole I in 1937 showed that ice from the North Pole moves straight into the Greenland Sea.

The first statements re the anticyclonic (clockwise) ice-drift in the region north of Alaska are contained in the scientific results (1909) of the Russian polar expedition of 1900-1903, led by E. V. Toll. They even indicate the approximate center of this movement, namely $83-85^{\circ}$ N $160-170^{\circ}$ W. The anticyclonic ice-motion in the region north of Alaska is also shown on

* See M. V. Lomonosov, Complete Collected Works, Vol.6, Academy of Sciences Press, 1952, pages 168, 400.

charts compiled by the author of the present article.*

The first unchallengeable proof that this motion does exist is, it would seem, the drifts of the ice-islands (see Fig.2).

Another proof of this motion is the following. In April of 1950, a Soviet drift station, which was given the name of Station North Pole II, was established at $76^{\circ}10' \text{ N } 167^{\circ}00' \text{ W}$. After a year in operation, by which time it was at $81^{\circ}33' \text{ N } 162^{\circ}01' \text{ W}$, the station was evacuated by aircraft. Tents and other visible objects were left on the ice-field. In the spring of 1951 this ice field was re-examined by our scientists. It was at $75^{\circ}10' \text{ N } 176^{\circ}05' \text{ W}$; that is, almost in the area where the station had commenced its work. Thus the station's ice field had in four years' time traced out a closed clockwise orbit.

Almost simultaneously with the finding of the ice-islands, Soviet scientists made a major discovery, which upseed many of our ideas about the bottom topography and geological history of the Arctic Basin. The expedition of 1948 revealed that a mighty submarine mountain range extends from the New Siberian Islands in the direction of Ellesmere Land, a mountain range which rises 2.5 to 3 km above the floor of the Arctic Basin and divides this basin into two sectors, Atlantic and Pacific. From the Atlantic sector of the Arctic Basin the ice is carried into the Green. and S. i., while in the Pacific sector there is that anticyclonic ice-eddy the existence of which had been announced, as we have seen, by Russian scientists at the very beginning of the 20th century.

One consequence of the characteristic circulations in the Atlantic and Pacific sectors of the Central Arctic is that between meridians 0° and 60° W there is formed a zone of open water leads, all lying in the direction from Franz Josef Land toward Ellesmere Land. These open leads have been observed repeatedly by Soviet explorers.

Since in the Atlantic sector the speed of the ice-drift is increasing as we approach the straits between Spitsbergen and Greenland, here the amount of open water between the drifting floes is also increasing. In the Pacific sector, on the other hand, the result of the anticyclonic movement is that the ice tends somewhat toward the center of this movement. Consequently almost no open water is observed here. The only exception is polynias outside the shore ice, such as Peary's "big lead"; polynias which open out during offshore winds and close up during onshore winds.

The drift of sea ice is usually due to many factors. The most clearly expressed influence on the drift is that of the wind.

Nansen spent a good deal of time in studying every aspect of the Fram's drift. He noted that the ice-fields of the Central Arctic respond

* See N. N. Zubov, In the Center of the Arctic, Northern Sea Route Authority, 1940, page 190; Arctic Ice, Northern Sea Route Authority, 1945, Fig.160 /DRB translation T 14 R7; In the Center of the Arctic, Northern Sea Route Authority, 1948, page 341. No indications of this anticyclonic movement have been found by the author in any other sources.

very quickly to the wind, and change their direction of motion in conformity with changes in the wind speed and direction; that the velocity of the ice-drift is approximately one fiftieth of the velocity of the wind causing this drift; that the direction of drift in the Northern hemisphere inclines 30° to the right of the wind direction. The last fact Nansen ascribed to the deflecting effect of the earth's rotation. This perfectly correct explanation later became the basis of the modern theory of currents in the sea. The conclusions at which Nansen arrived have since then been confirmed time and again, and particularly in the drifts of Station North Pole I and of the Sedov.

The Sedov drift took place at a time when there existed in the Arctic a network of Soviet meteorological stations, which made possible a quite accurate appraisal of the synoptic picture throughout the drift. Analysis and comparison of this drift with atmosphere pressure distribution charts compiled by the Weather Bureau enabled me to derive certain general rules for ice-drift

It became clear that the ice-drift proceeds along the isobaric curves (that is, lines of equal atmospheric pressure), in such direction that, in the northern hemisphere, a high pressure region is on the right and a low pressure region on the left of the drift course; the ice drifts at a speed proportional to the pressure gradient, or in other words the drift velocity is inversely proportional to the distance between isobars.

These rules, which make it possible to trace out the wind-drift of the Central Arctic ice-fields, have found a broad application in the solution of many problems relative to ice-drift.

Fig. 4 shows the distribution of mean atmospheric pressure in millibars for the winter season, and Fig. 5 the same for summer.* The arrows on the two charts represent the theoretical ice-motions (along the isobars). The eastern closed circulation (clockwise) and the western movement into the Greenland Sea are both clearly seen.

It is curious to note that the 1020 mb isobar (in winter) and the 1015 mb isobar (in summer), which determine the anticyclonic movement of the ice in the Pacific Sector of the Arctic, intersect the coastal line in the region between Greenland and Ellesmere Land. Since the ice must drift according to these isobars, and the shores are in the way of this drift, the northern shores of Ellesmere Land will naturally be subjected to a continual pressure of the Arctic ice, and this is likely part of the explanation of both the size and the corrugation of the ice-shelf on these shores.

In the same way we may explain, for instance, the fact that Ice-island T-1, upon approaching the shores of Ellesmere Land at the end of 1951, ceased to drift farther.

There is no definite information on the fate of T-2. Apparently this ice-island too is now somewhere on the coast of Ellesmere Land.

* From the book "In the Center of the Arctic" by N. N. Zubov, Northern Sea Route Authority, 1940, pp. 201, 202.

T-3, as already said, had at the beginning of the present year come so close to Ellesmere Land (its position on May 5th, 1954, was $84^{\circ}35' N$ $81^{\circ}00' W$) that the Americans evacuated the meteorological station which they had established on it.

Fig.6 shows the theoretical drift of the Arctic ice in 1938. The anticyclonic eddy in the eastern part of the Arctic Basin is clearly seen.* The round dots on this chart mark the January 1st positions of ice-fields, the movements of which were traced until the end of the year. The drifts were calculated by M. M. Somov from the monthly atmospheric pressure charts; in this work he employed the above-stated rules, plus calculating formulae worked out for the purpose by myself in collaboration with Somov.

The rules which I established are on the whole valid only for the drift of ice-fields of no great thickness. Icebergs and ice-islands, which may have very considerable thicknesses, have a somewhat different drift.

What is involved is that the velocity of sea currents as a rule decreases with depth, while their angle of deviation, due to the deflecting force of the earth's rotation, increases. Hence the more water an ice-mass draws, the slower it drifts and the more it deviates from the wind direction. Hence the drift-course of an iceberg or ice-island differs a little from that of the surrounding floes, and for this reason we always see, around ice-islands, polynias of more or less size, while at a distance from these ice-islands no polynias are to be seen.

Since ice-masses of deep draft (icebergs and ice-islands) are more strongly deflected from the wind direction than ice-fields are, the result is that in regions of high atmospheric pressure they move gradually toward the center of the system, while in regions of low pressure, on the contrary, they move toward the periphery. As we have seen, the three ice-islands discovered in 1946 to 1950 were drifting in an anticyclonic region, and were therefore, one might say, pulled into it, and could have gotten out of it only under a particular combination of various circumstances.

Calculations of the general ice-drift for a number of years, made by myself and Somov in collaboration, have shown great fluctuations, positional and descriptive, in the barometric topography, both from season to season and from year to year. As a result of these fluctuations, individual ice-fields, icebergs and ice-islands may be thrust out of one oceanic eddy into another. It would seem (this idea has not yet been verified) that in the middle of the 1940's the synoptic and oceanological factors added up in such a way that ice-islands broke off from the Ellesmere shelf, described closed orbits in the clockwise direction, and have now returned to the region where they began their drifts.

At the present time there is, apparently, not a single ice-island of any size left in the central regions of the Arctic. Whether the ice-islands which have completed their orbits will in the near future recommence their drifts, or whether new ones will break off from the corrugated shelf-ice of Ellesmere Land ... these are questions which so far it is impossible to answer.

* See N. N. Zubov, In the Center of the Arctic, Northern Sea Route Authority, 1948, page 361.

Translated from Priroda, 1955, 3, 89-92.

THE ORIGIN OF THE FLOATING ICE-ISLANDS

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Over the last fifteen years, Soviet airmen have discovered, in various regions of the Arctic Basin, numbers of drifting ice islands, with areas measured in hundreds of square kilometers.

V. F. Burkhanov, Director of the Northern Sea Route Authority, has brought forward a great deal of data to show that giant icebergs have been encountered in the Arctic in past years. These data provide a satisfactory explanation for the unexpected discoveries and mysterious disappearances of a number of dubious Arctic "land-masses": What happened was that explorers and travellers mistook floating ice-islands for land.*

However, the problem of the origin of the enormous ice-islands is still far from being solved.**

Some aerial photographs were shown us by M. Ya. Molin, in which there is an ice-island about 12 km long, lying in a fjord of one of the islands of Severnaya Zemlia. From these photographs we constructed a diagrammatic chart of the fjord (Fig.1), in which one may clearly see the spatial relationships between:

The glacier streams creeping down into the fjord from the ice-crowns of the island (beyond the edges of the chart);

Land not covered with continental ice;

The body of the fjord, covered with sea ice and half filled with large and small icebergs.

Among the masses of continental ice, our attention is drawn to the huge "main" glacier stream (MG), forming an ice-fall over a very sizable and very steep section of its bed, which is for the most part the bottom of the fjord. This glacier stream does not take up the whole breadth of the fjord; it is apparently restricted by certain longitudinal outcroppings in the underwater topography. On the right and more particularly on the left of the lower part of the glacier stream, between it and the shores of the fjord, there are numerous large icebergs (up to 4 km in length) and a lot of small ones (a). They have been formed by break-up of the peripheral parts of the main glacier, a break-up caused by the dissected relief of the bed, and in particular by the presence of a number of nunataqs (N).

* See V. Burkhanov, New Researches of Soviet Scientists in the Arctic, Pravda, May 16, 1954.

** See N. N. Zubov, The Arctic Ice-islands and How They Drift. Priroda, 1955, 2, 37-45. (Here translated.)

The largest iceberg A (length as much as 12 km and breadth about 4 km) lies ahead of the main glacier front and takes up a good fraction of that part of the fjord which is not occupied by the glacier. This iceberg is streaked with a network of streams and has a lot of ponds (up to 0.3 km long), which follow the irregularities of the ice topography. The height depth of the underwater * part of the ice-island varies from 5 to 20 m; in the middle it has a huge fissure through it, which, like the water surface around the iceberg, is covered over with young ice.** From the tail part of iceberg A and from its left-hand edge, a few smaller ice-islands and bergs have split off, forming a sort of buffer between the giant berg and the main ice-stream moving against it.

On the western shore of the fjord, several smaller lateral glaciers LG₁, LG₂, LG₃ descend, depositing a great quantity of morainic material in the fjord.

But how was the giant berg formed? Why has it stuck in the fjord, and has it been there long?

The position of this 12-kilometer iceberg points indubitably to the fact that only quite recently it constituted the front of the main glacier, a front which had pushed far forward, up to the very throat of the fjord. The final obstacle which the glacier front could not overcome was, apparently, the moraine-accumulations deposited in the fjord by glacier LG₃. Because of this, plus the underwater moraine of glacier LG₂, the main ice-stream between LG₂ and LG₃ must have been, for some period of time, a sort of ice-bridge, with the submerged moraines of the lateral glaciers for its piers (Fig.2). We may suppose that because of the great depth of this part of the fjord the ice-bridge did not fill it right to the bottom, as the upper part of the glacier does; meanwhile, the underwater moraine in the throat of the fjord did not allow the projecting part of the glacier to get into a floating condition. It could not remain in such a position for very long, because of the greater and greater thrust of the ice-mass creeping down into the fjord; moreover the semi-floating part was subjected to a gradually increasing hydrostatic pressure lift due to the melting-away of its underwater part. The main glacier therefore broke, chiefly over the submerged moraine-deposits of lateral glacier LG₂; here two fissures formed, which melted their way through the whole thickness of the ice, and which obviously corresponded to the left and right lateral moraines of glacier LG₂ (Fig.2, II). Between these two fissures a number of large and small "buffer" icebergs were formed, lying between the new front of the radically truncated main glacier and the huge off-splut iceberg A. This, it seems, is in broad outlines the mechanism whereby the front part of the main glacier was turned into the giant ice-island. Because of its considerable draft (not less than 100 m), the ice-island can not get out into the open sea until it has melted down enough to pass unhindered over the moraine-deposits in the throat of the fjord (Fig.2, III).

* Should this be "above-water part"? (Translator.)

** Just the same picture is presented by the floating ice-islands observed in the Arctic Basin, which frequently attain even greater size.

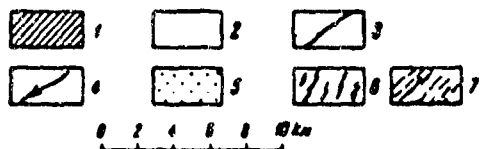
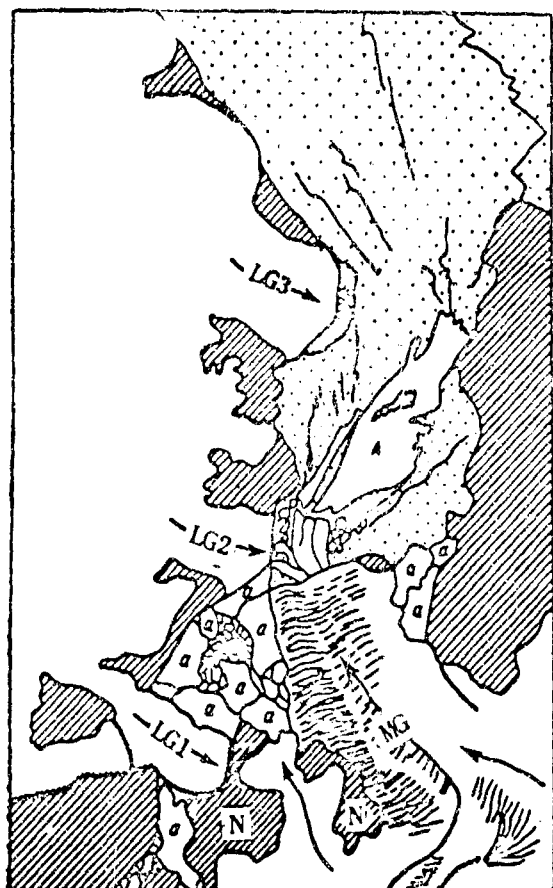


Fig. 1. Continental ice, icebergs and sea ice in a fjord on one of the islands of Severnaya Zemlia.

1. Land areas free of glaciation;
2. Glaciers and icebergs;
3. Surface moraines;
4. Direction of movement of the different ice-streams;
5. Sea ice;
6. Fissures and polynias in sea ice;
7. Fissures on surface of main glacier (MG).

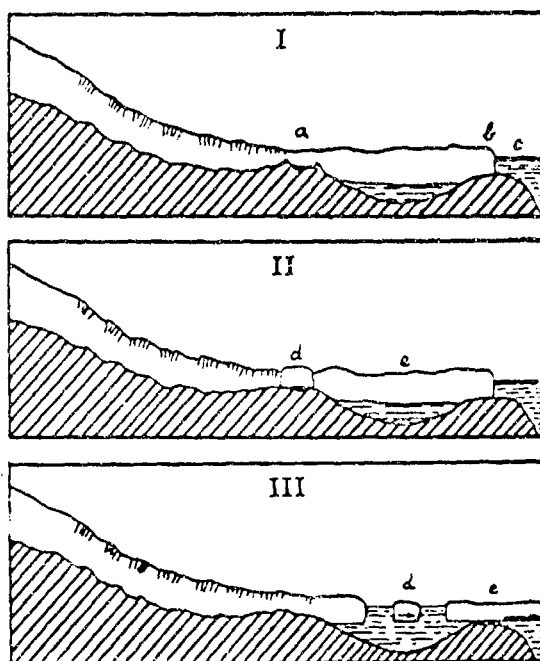


Fig. 2. Successive stages (I, II, III) of formation of giant icebergs in a fjord similar to that depicted in Fig. 1.
 a - Place where lateral glacier LG₂ descends.
 b - Throat of fjord.
 c - Sea ice.
 d - Buffer berg.
 e - Giant berg.

In the fjord, the ice-island is being worn down by the waves, by the tidal currents and by the motions of the sea ice; also by the pressure of the main glacier thrusting a new tongue out into the fjord. This pressure is gradually breaking up the buffer bergs and the peripheral parts of the giant berg; it is in fact responsible for the huge fissures and long narrow polynias radiating over the sea ice from the northern and western sides of berg A. It appears that ice-islands, if something delays the process of their melting down, may be completely destroyed in situ, without ever getting out of the fjord.

All this makes it possible to suggest that giant icebergs are formed in those Arctic regions where a present-day ice-sheet is associated with a fjorded shoreline, half buried under the continental ice.

If the shoal-bound or semi-floating shelf-ice which forms over long stretches of the shores of many Arctic islands were capable of producing giant icebergs, then these giant icebergs, and not small ones, would make up the bulk of the drifting ice of continental origin. The facts, as we see, indicate the contrary.

A fjord origin for the ice-islands of the Arctic basin will explain very well their rather dissected relief, the network of streams, and the occasional moraine-cover. All these are in no wise typical of ice-sheets descending in a broad front to the sea.

In favor of the fjord hypothesis we have the entire agreement between the sizes of the largest ice-islands of the Arctic Basin, which are up to 35 km in length, and the sizes of the floating parts of the glaciers descending into the fjords of Greenland and Ellesmere Land. For instance, in Peterman Fjord there is a glacier which forms a floating ice-tongue 40 km long.

Giant icebergs of somewhat smaller size may be produced on the islands of Novaya Zemlia. In Franz Josef Land, fjords suitable for the formation of anomalously large icebergs exist on one of the islands only, namely George Land, although these fjords are considerably shorter than those of Severnaya Zemlia. It is not out of the question that giant icebergs may be formed in some fjords of the Kara Sea coast of the northern island of Novaya Zemlia; likewise on the western shores of Spitsbergen.

Ice-islands are not an exclusive property of the Arctic Basin. According to V. Kh. Buinički's data, * icebergs up to a hundred or more kilometers in length (!) have been known in Antarctic waters from the middle of the last century. However, as in the Arctic Basin, the common-run icebergs of the southern hemisphere are not very large; their average length is about 400 m. Hence the formation of the Antarctic ice-islands can scarcely be ascribed to break-off from the edges of an ice-sheet descending at a gentle angle into the ocean. It is more natural to suppose that the unique ice-islands of the Antarctic are broken off from the gigantic ice-tongues thrust out by the even more grandiose glacier streams which are known to exist on comparatively restricted stretches of the coast. Thus, for instance, in Adelie Land there are valley-glaciers which thrust out onto the open sea ice-tongues as much as 130 km (!) in length.**

* See V. Kh. Buinički, *Antarktika*. Geografiz [Geographical Press], 1953.

** See S. V. Kalesnik, *Obshchaya Gliaciologiya* [General Glaciology], Ushpedgiz [Educational and Pedagogical Press], 1939.

In both the northern and southern hemisphere ice-islands are formed by the breaking-off of glacier ends, not the edges of ice-sheets. Ice-sheets which descend into the sea along a broad front have very small speeds of movement, usually some tens of meters per year. Glacier streams, on the other hand, have speeds which not infrequently amount to some kilometers per year. Thanks to this, the glacier streams are capable of advancing for considerable distances out to sea faster than conditions can be established for their destruction.

In the foreign press, and also in ours, it has been asserted that the ice-islands have been preserved in the Arctic Basin from the time of Quaternary glaciation. In particular, V. F. Burkanov states that one of the sources of the ice-islands was the massive Quaternary ice-sheet of Franz Josef Land. Similar notions were indeed put forward somewhat earlier by D. G. Panov (see *Priroda*, 1953, 2, p.113), who in turn borrowed them from Emery and Revelle.*

It seems to us that the purely speculative hypothesis of the ice-islands as "relics" is quite unwarranted. The origin of giant icebergs is perfectly explainable in terms of the kinetics of the present-day glaciers in high latitudes. Moreover, the marked shrinkage of the present-day continental ice in the Arctic, as compared with that of the Pleistocene, does not accord with the idea that icebergs from that period could have been preserved until our day. Indeed conditions for the preservation of a land glaciation are incomparably more favorable than those for the preservation of icebergs, which have the bulk of their ice immersed in the water and are eroded by it all the year round.

The giant icebergs of the Arctic Basin are comparatively recent formations, which apparently cannot remain in existence more than a decade or two. This is indicated by their comparatively flat topography, and by the very little altered morainal cover frequently preserved on their surfaces.

It therefore seems to us that all these ice-islands, caught in closed circulations dependent on the sub-surface currents in the Arctic Basin, have a single destiny: to be broken up into a swarm of quite ordinary icebergs and ice-blocks. The drift of these, as is well known, is guided by the less complicated system of surface currents, which brings them to a mass exodus from the Arctic Basin into the northern Atlantic, where they finally degenerate.

All the above testifies that the ice-islands are recent formations, not just in the geological sense, but even in the ordinary sense of the word.

For further work on the problem of the genesis of ice-islands, special research will be needed; in particular, the continuous photographing and rephotographing of the numerous fjords of our Arctic islands.

* *Bull. Geol. Soc. America*, 62 (1951), 3, 325. (Translator.)